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An Anthropomorphic Design for Minimally Invasive Surgical System based on a Survey of Surgical Technologies, Techniques and Training

Antonia Tzemanaki [1, 2]*
Peter Walters [1, 3]
Anthony Pipe [1, 2]
Chris Melhuish [1]
Sanja Dogramadzi [1, 2]

{1} Bristol Robotics Laboratory, Bristol, UK
{2} Department of Engineering Design and Mathematics, University of the West of England, Bristol, UK
{3} Centre for Fine Print Research, University of the West of England, Bristol, UK

*Correspondence to: Antonia Tzemanaki, Bristol Robotics Laboratory, T Building, Frenchay Campus, BS16 1QY, UK.
E-mail: antonia.tzemanaki@brl.ac.uk

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Abstract

Background Over the past century, abdominal surgery has seen a rapid transition from open procedures to less invasive methods such as robot-assisted minimally invasive surgery (MIS). This paper aims to investigate and discuss the needs of MIS in terms of instrumentation and to inform the design of a novel instrument.

Methods A survey was conducted among surgeons regarding their opinions on surgical training, surgical systems, how satisfied they are with them and how easy they are to use. A concept for MIS robotic instrumentation was then developed and a series of focus groups with surgeons were ran to discuss it. The initial prototype of the robotic instruments, herein demonstrated, comprises modular rigid links with soft joints actuated by shape memory alloy helix actuators; these instruments are controlled using a sensory hand exoskeleton.

Results The results of the survey, as well as the ones of the focus groups, are presented here. A first prototype of the system was built and initial laboratory rests have been conducted in order to evaluate this approach.

Conclusions The analysed data from both the survey and the focus groups justify the chosen concept of anthropomorphic MIS robotic instrumentation which imitates the natural motion of the hands.

Keywords minimally invasive surgery; robot-assisted surgery; survey; focus groups; multi-fingered instruments; shape memory alloy actuators; hand exoskeleton.

Introduction

Minimally invasive surgery (MIS) is performed through small incisions on the patient's body instead of one large opening (as in conventional open surgery). Advances in MIS over the last decade have led to a convergence of techniques available for treatment of a number of conditions. MIS procedures are becoming more common in hospitals (e.g. laparoscopic hysterectomies increased from 17.7% to 46% during 2006-2009 [1]) because of their numerous advantages, such as decreased blood loss and pain, cosmetic results, shorter hospital stay and thus, lower cost [2]. Robot-assisted MIS (R-A MIS, also referred to as robotic surgery) offers the possibility of improved precision and dexterity, helping surgeons overcome limitations of current surgical tools [2]. The MIS techniques and routines differ significantly, depending on which part of the body is operated on (e.g. abdominal surgery, neurosurgery etc.). Our research focuses mainly on surgery of the lower abdomen. Prostate cancer is the fourth most common cancer (12%) and the most common cancer in men accounting for 25% of all cases of cancer in males in the United Kingdom (2009) [3], while bowel cancer accounts for 13% of all cases of cancer in the UK (2009). In addition, cholecystectomy (gall bladder removal) is one of the most frequent procedures, more than 80% of which is undertaken using MIS [4].

Laparoscopic MIS techniques – learning and ergonomics

Acquisition and mastery of basic laparoscopic skills precedes the performance of advanced laparoscopic operations, and hence, training surgeons in minimally invasive surgical procedures is becoming increasingly time consuming [5]. When learning a new procedure, performance tends to improve with experience. The learning curve phase constitutes a very stressful part of a surgeon's career, while it is extensively cost inefficient and induces complications for the patients [6].

Studies have shown [7-8] that surgeons frequently report problems such as neck, shoulder/arm, hand/wrist and back pain/stiffness, while suffering from mental fatigue after carrying out a series of laparoscopic procedures. It is also mentioned [7] that the surgeons are not able to perform precision motions and that they find the instruments awkward to manipulate. The adjustability of the device is a significant factor, and as it has been reported in [9], laparoscopic instrument users with smaller hand size have difficulty in operating them and also experience musculoskeletal problems. Increasingly, robotic surgery is aiming to replace manual laparoscopic surgery. Are robotic systems adjusted to the surgeons' needs and comfort?

Robotics and MIS

The use of surgical robotics could enhance and shorten the learning process. Big screens and better vision lead to better collaboration and communication between the surgeon and the medical staff, which also means that the trainees can learn faster. In [10-11], it is argued that the training of a new surgeon has to be as intense and efficient as possible, while [12] emphasizes the need for a simulator that could provide adequate training, equivalent to using the actual robotic system.

In order to not only improve the patient's safety but also the surgeon's experience, great effort is being put into designing new instruments and systems for MIS. The benefits that robotics could bring to the medical field are manifold, however, a number of questions remain. Do the existing systems satisfy their users? Which surgical techniques are of preference i.e. the ones that robotics should focus on? Has the surgical training experience improved with the use of technology? Do surgeons suffer from bad ergonomics? Relevant information can be obtained by surveys such as [13] which investigates the usefulness of a surgical teaching simulator or [14] which examines to what extent surgical residents participate in operations and if they are satisfied with their MIS training experience. Similarly, [15] investigates the effectiveness of training on robotic surgical procedures, while in [16] more general needs of the operating room of the future are addressed, with focus on the interoperability of devices, the improvement of the surgical systems and their integration with the surgical workflow.

It is clear that further research needs to be conducted so that it can be determined how surgeons adapt to the new robotic techniques and how challenging the transition from invasive to minimally invasive procedures is. Following on from this, we have conducted a survey to gather surgeons' views on surgical training and existing surgical procedures. After the completion of the survey, a concept for MIS robotic instruments was developed.

Anthropomorphic MIS instrument design

Our proposed concept of the instruments has been previously introduced in [17], where we presented a concept for hand-like instruments, each carrying an articulated 3-finger system that imitates the surgeon's fingers' movements. The anthropomorphic system design aims to reduce the 'cognitive gap' between the way that instruments are manipulated and the surgeon's natural hand movements. The way that the instruments are controlled affects not only their efficacy, but also the ergonomics and the learning process for the surgeon. The master controls of the Da Vinci Surgical System manipulate a simplified gripper attached to a 3-DOF wrist. In a very similar way, the Phantom Omni haptic device is used to control surgical instruments in various other designs of MIS instruments [18]. If the instruments to be controlled are more complex, more complex master devices are required.

Systems for motion capturing of hands span from on-the-hand hardware with finger position capturing, such as data gloves and exoskeletons, to external imaging systems based on intensive image processing and often covering a limited field of view. Data gloves, used for similar tasks, are expensive and generally lack durability [19]. Besides being non-adjustable and requiring calibration for each user, data gloves do not offer detailed joint tracking. In [20], a wrist-worn real time hand tracker is proposed, which avoids burdening of the hand with extra load. Limitations include occlusions resulting from overlapping fingers. Besides finger tracking, wrist rotation and bend tracking is very important especially during surgical tasks. However, these cannot be modelled using a wrist-worn tracker or a data glove.

Finally, we report here on the development of a lightweight and adjustable hand exoskeleton that can sense movements of the surgeon's finger's joints and translate it to movements in the joints of an instrument, such as the one we presented in [17]. Most exoskeletons in the literature are aimed at actuation of hands or arms [21], often ending up being bulky and heavy. By removing all the motors and encoders, the design can be simplified. This concept was then evaluated using a series of focus groups with surgeons. Initial prototype of the instruments and results gathered through experiments are presented, as well as the design of an initial prototype of a hand exoskeleton for control of the said MIS instrumentation.

Materials and Methods

Preparation of the questionnaire

The survey was designed to establish current experiences of surgeons and what limitations they face in current surgical procedures. An ultimate goal was to gather sufficient requirements to be able to define a new MIS instrumentation concept by obtaining qualitative and quantitative (statistical) data.

Forming the questions

The questionnaire comprised a selection of both "open-ended" and "closed-ended" questions. In order to meet the previously mentioned goals, it was necessary to elicit information including the following:

- Duration of laparoscopic/robotic training
- Laparoscopic/robotic training complexity/difficulty
- Difficulty in adjusting from open surgery to MIS
- Satisfaction with the cost/performance of the existing systems
- Willingness to adapt to new methods/instruments
- Preference of surgical techniques
- Posture and ergonomic issues
- Preference in terms of surgeon-system interfaces

There were two methods used for the questionnaires: i) to hand them directly to the participants in paper form giving them an interval of two weeks before collection and ii) to create an electronic version and send the web link via email to surgeons. Questionnaires were also translated into the language of destination before being sent.

Eleven questionnaires were first sent to a target group as a pilot in order to ensure that the questions were not misinterpreted and that they were answered in a useful manner. No such problems had arisen among the seven responses, and so, the survey moved to the main phase. According to the respondents of the pilot phase the questionnaire took between 5 and 20 minutes to complete.

As it is suggested in [22-24], the questionnaire started with easy questions, going from general to more particular ones. The most important questions were placed towards the beginning, while the demographic and personal ones last. Different types of closed-ended questions, such as multiple choice, Likert-scale and rating scale were used in order to make it less monotonous and repetitive.

Population sample

The respondents included 35 surgeons, from the UK (45%), Spain (43%), France (6%), Japan (3%) and USA (3%), of age between 35-64 years old, of both genders (the ratio of women to men being 1:4) and with various experience (seniority) in at least one MIS technique, while their surgical specialties included general surgery, urology, gynaecology, digestive system and bariatric surgery. Demographic data regarding their age and experience, as well as the level of seniority in open and MIS surgery as they would personally rate themselves are displayed in Figure 1. The outcome of the survey is presented in the Results section.

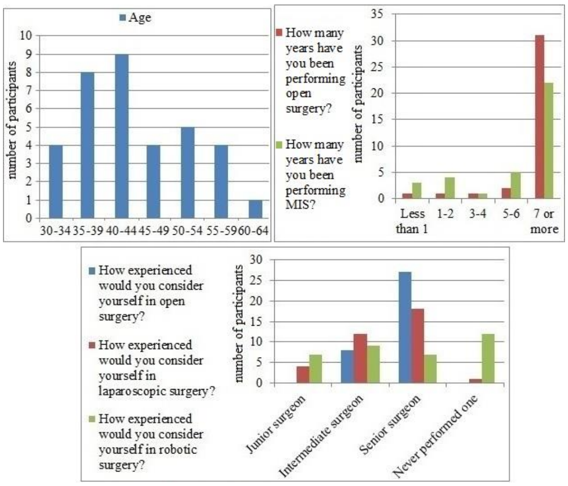

Figure 1. Age and Experience of the participants

Focus groups

Two focus groups were conducted. The first one comprised one moderator and four surgical registrars from the Bristol Urological Institute, UK. The focus group took place outside their working hours and lasted 1.5 hours. The second focus group, lasting 25 minutes, included two senior surgeons (Cambridge, UK and Verona, Italy) and two moderators, one of which is a surgeon.

Each session was recorded in audio/video, then transcribed and processed using content analysis [25]. Deductive category application [26] was initially used to code the transcript with predetermined themes related to the concepts that were read. Following the first method, inductive category development [26] was applied to code ideas not previously identified, but deduced in a step-by-step manner.

Results

Survey outcome

Surgical systems

In one of the questions, the participants were asked to list the main benefits (Figure 2) of the Da Vinci Surgical System. Their answers praised it for its 3D vision (43% mentioned this in their list), articulation of instruments (31%), intuitive manipulation (28%) and better precision (23%) compared with traditional laparoscopy. The following question was regarding the cost of the Da Vinci system, in terms of its cost-performance balance (Figure 3), to which more than 45% responded that the system is too expensive to buy. 40% chose that it is expensive but worth buying, while no participant believed that the price is fair.

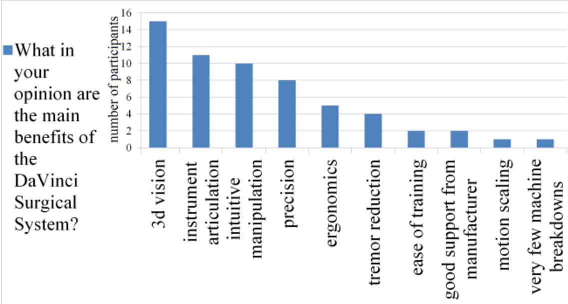

Figure 2. Main benefits the Da Vinci Surgical System

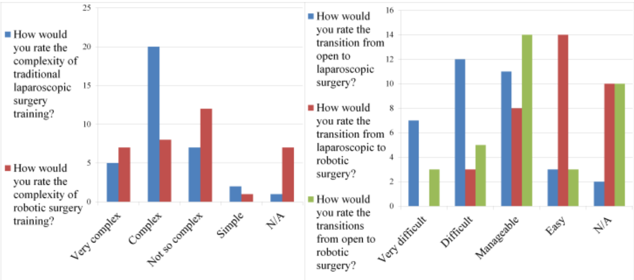

Figure 3. Cost/Performance balance of the Da Vinci Surgical System

Surgical training and techniques

In questions with respect to single-port access (SPA) surgery, 32 out of 35 surgeons answered that they prefer multi-port MIS to single-port (Figure 4). Their responses regarding the benefits of SPA (compared to multi-port) included mainly 'more cosmetic results' (21 surgeons) and 'less incisions to be healed' (6), while two participants considered it to have no benefits. The drawbacks included difficult operation of instruments (22), increased duration of operation (6), limited movements and poor dexterity (5), poor ergonomics (4) and increased risk of hernia development (4), a fact also discussed in [27].

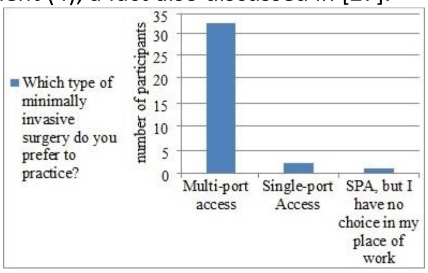

Figure 4. Preference in laparoscopic technique

When asked how complex they considered their laparoscopic surgery training to be, 25 surgeons responded with 'very complex' or 'complex' opposed to only 7 surgeons believing that it is 'not so complex', while the numbers regarding robotic surgery were 15 and 12 surgeons respectively (Figure 5). This shows that the training for robotic surgery was generally considered simpler. However, most of the participants had previously undergone training for laparoscopic surgery, which possibly affected their answers since they had already been accustomed to the basic concept of MIS. Therefore, the issue of the transition from one surgical technique to another needs to be discussed and is also illustrated in Figure 5. Although robotic surgical techniques differ from the ones used in laparoscopy, only 3 participants found the transition from laparoscopic to robotic surgery to be difficult. In addition, surgeons seemed to be divided in two categories: those who had experience in basic or advanced laparoscopy and then moved on to do robotic training, and those who were trained directly in robotic surgery after they had completed their basic open surgery training. After being trained in open surgery, 19 surgeons found it 'very difficult' or 'difficult' to get adjusted to laparoscopy, in contrast to only 8 surgeons having trouble to adjust from open to robotic surgery.

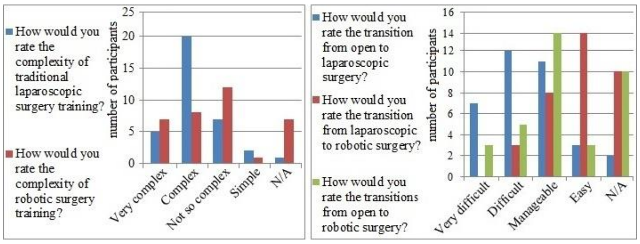

Figure 5. Surgical training and transitions between surgical techniques

Ergonomics in robotic surgery

Figure 6. Posture during MIS

Figure 6 represents the data concerning the surgeons' satisfaction with their posture during surgery. Despite the fact that 25 surgeons stated being 'very happy' or 'happy' with the posture during laparoscopy, we can see on Figure 7 that 21 participants mentioned preferring a seating position, while only 3 favored standing. One can deduce from the above that although they are relatively satisfied with current standards, they are open to improvements.

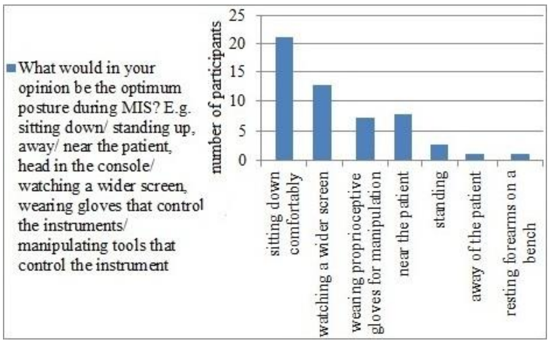

Figure 7. Preference in position and posture during surgery

Consequently, a rating scale of 1-4 was used to determine how willing they are to adapt to new methods that may change their routine during MIS (1=I do not want to adapt to a new concept, 4=I am very happy to try), such as an anthropomorphic design of tools with an alternative master (control) system and how willing they are to try instrumentation that does not change their routine (1=I do not want to try new tools, 4=I am very happy to try new tools). Results presented in Figure 8 show that in both cases they were willing to try new instruments even in the case that this meant having to adapt to a new routine. The fact that the majority replied positively indicates again that there is a high degree of anticipation for a new concept and an overall lack in adjustability of the existing systems.

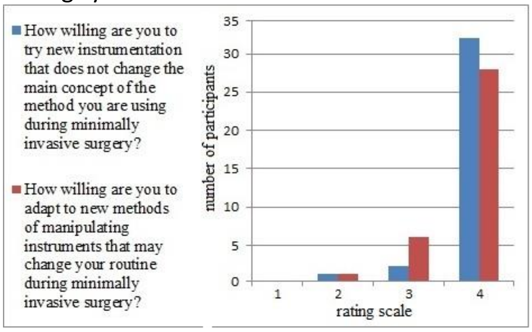

Figure 8. Willingness to adapt to new methods/new instruments

The previous discussion suggests that a new concept of instruments for robotic surgery would have to separate itself from the design of existing laparoscopic tools. Mitigating the learning process would be a significant aspect of the system, which could be achieved by enhancing the ergonomics and making the manipulation even more intuitive.

Novel system concept

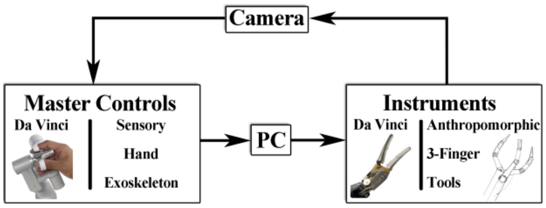

Figure 9. System schematic and comparison with the Da Vinci main components

The survey presented in the previous section helped to define inadequacies of the existing systems and consequently form a better understanding of how they could be improved. Based on the results, a novel concept for surgical robotic instrumentation was designed. The overall system layout is similar to the master-slave system of the Da Vinci and consists of two basic subsystems: the master controls and the instruments. The surgeon is using the master controls (an exoskeleton) to manipulate the instruments. The proposed design for the instruments that we presented in [17], involves a three-finger robotic mechanism, which imitates the movements of the surgeon's thumb, index and middle finger. Figure 9 explains the relationship between the various components in comparison with the main parts of the Da Vinci Surgical System.

Focus group discussion

The chosen design aims to combine the best aspects of the approaches in use at the moment (open, laparoscopic and Da Vinci surgery). In order to further evaluate it, as well as confirm the survey results, two focus groups were conducted.

The participants were given three concepts to read. The first concept presented a surgeon claiming that a patient should have open surgery as treatment to his condition, while in the second one a different surgeon counter-proposed that the patient should choose robotic surgery. The major themes emerging from these two concepts were:

- advantages of open compared to robotic surgery
- advantages of robotic surgery compared to manual laparoscopy
- differences of the techniques in their learning curve

The third concept described in detail the system design of the previous section and instrument design of [17] and the emerging themes included:

- value of hand-like movement
- potential usage and applications
- suggestions/alterations

The questions for each of the three concepts were: What do you think is good about the concept? What do you think is bad about the concept? What do you think could be done differently? The following paragraphs are analyzing the topics mentioned above.

Robotic vs. open surgery

The participants claimed that the duration of a procedure is longer when done robotically-assisted rather than using the open technique. They partially attributed this to the limited field of view (also reported in [28]) and range of movement of the surgical robot because its arms are rigid and often clash with each other, but also to the bulkiness of the system. The surgeon has a relatively restricted field and it is not easy to replicate open surgery techniques. In addition, the lack of tactile feedback during robotic surgery was considered a big issue, as otherwise "you are not going to be able to use the fingers to do what the fingers do".

With respect to complex procedures, the participating surgeons said that surgeons generally use the open technique, while a minority uses traditional MIS and even less surgeons practice R-A MIS. This was ascribed to what is considered as the golden standard for a surgical procedure at a given time. The golden standard changes over time and is directly connected to the statistical success of a certain technique and indirectly to its cost. “If R-A MIS was less expensive, conventional laparoscopic surgery could become a thing of the past”. Robotic MIS requires a big investment, as hospitals have to also disburse funds for the disposable robotic instruments. However, medical benefits of the system have not been clearly proven yet, as there have been no randomized trials comparing the Da Vinci surgery to manual laparoscopic techniques [28]. In favor of robotic surgery, reduced pain and blood loss, quicker recovery and better cosmetic results were mentioned.

Robotic surgery vs. manual laparoscopy

The main advantages of robotic compared to conventional MIS were narrowed down to improved ergonomics and vision. The 3D vision was especially emphasized as being an asset that foregrounds robotic surgery, while conventional MIS (e.g. for prostatectomy) is a longer but more tedious process because the surgeon has an unnatural posture often for more than three hours.

Robotic surgery was also considered as being more intuitive and considerably simpler and straightforward to familiarize with, compared with traditional MIS. High articulation of the instruments, flexible movement as well as quicker recovery, less blood loss and less post-operative required analgesia were also added to the advantages of R-A MIS, while the fulcrum effect was mentioned as a downfall of traditional MIS.

Learning curve

The learning curve for MIS was thought of as longer (implying that is harder to learn the MIS technique) than the one for open surgery. The reason was believed to be that surgeons are trained first in open surgery and are not exposed to MIS techniques until later in their careers, while participants also associated this to what is considered as golden standard and the way surgery has evolved over the years (surgeons would try MIS techniques on simple procedures and only when MIS became popular regarding these specific procedures, would the technique be tried more widely).

When comparing traditional with R-A MIS, however, the learning period of the first was viewed as being much longer than the latter’s. This was attributed to better ergonomics, ease of instrument control and enhanced vision during robotic surgery.

Feedback for the MIS instrument concept

Table 1 summarizes the main points of the discussion regarding the concept of a new instrument for R-A MIS. The participants supported the idea of a hand-like instrument by describing it as an extension of the fingers with added versatility and attributes that make it possible to perform tasks that the hands alone cannot do. Despite noting that tactile feedback would be very important, they commented more specifically on the actual movement of the instrument. They welcomed the idea of an instrument that behaves exactly like their hands and thought that its manipulation would come naturally. In addition, the ability to work symmetrically using both of their hands in the same way and to follow the natural curve of an organ would help them reproduce their movements during open surgery.

When talking about potential uses of such an instrument and its advantages over existing ones, the ability to perform more actions using a single hand was mentioned. The surgeon would be able to use two of his/her fingers for traction (thumb and middle finger) and the third (index finger) to dissect tissue, while the other hand (three more fingers) is used as a retractor for an organ. This would minimize the need for an assistant, as for example in the case of a cholecystectomy, where the assistant needs to retract the gall bladder and the surgeon is using both hands for traction and dissection. Furthermore, since the instrument’s fingers could be adapted to be used as three-link ones or just as forceps (by collapsing all links together but the last), the surgeon could use all available DOFs to grasp something of a bigger diameter (e.g. in bowel surgery) smoothly and without traumatizing it (e.g. ureter or liver) or collapse DOFs to yield a more traditional needle holder with strong tips.

The original idea of integrating a blade inside one of the fingers of the instrument was not popular among the participants. Instead, scissors were preferred, while the integration of a hook or irrigation system that comes out with the push of a button (or pedal) seemed very appealing.

Table 1. Feedback Summary

hand-like movement	Potential usage	suggestions/alteration
behaves the same as your hand	more actions using one hand	scissors preferred to a blade
natural movement of manipulation	traction using 2 fingers, cutting with the 3rd	integration of a hook
grasping without pinching/traumatizing	could be used as a retractor	integration of irrigation system
ability to work symmetrically	could be used both as grasper and needle holder	tips should be strong enough to hold a needle
ability to follow the natural curve of an organ	bowel surgery (big diameter object grasping)	
extension of the fingers with added versatility	ability to use all links or just tips	
reproduction of movement's during open surgery	smoother grasping (e.g. ureter)	
advantages of the hand plus tips able to perform tasks the hand cannot do	liver surgery, cholecystectomy (retraction with one, surgery with the other)	

Anthropomorphic instruments

Following the discussion and feedback from the focus groups, a first attempt to prototype the instruments was made. The scaled-up prototype is a robotic finger with an overall length of 9.7 cm (simulating the length of an average human finger) comprising three rigid links connected with two soft joints.

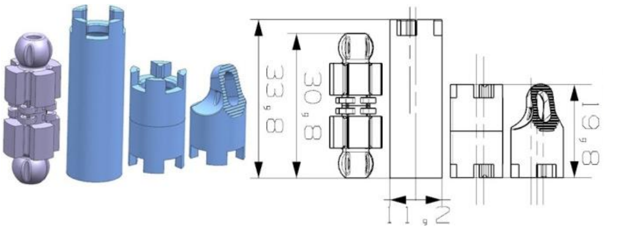

Figure 10. Links and joint of the finger in CAD software

All structures were designed in computer-aided design (CAD) software (Figure 10) so that each structure can accommodate shape memory alloy (SMA) helix actuators (Biometal Micro Helix, Toki, Japan). Actuation becomes possible using the property of the SMA helices to contract (up to 50% of their elongated length) when current passes through them. Each joint is actuated by one or two antagonistic pairs of helices, which enable motion in one or two Degrees of Freedom (DOFs) accordingly. The operation principle is shown in Figure 11. The SMA helix is elongated (by 200% of its original size) and then fixed into the structures. When the helix is heated and as it is contracting, two opposite forces from either end are acting, resulting in the joint being bent (Figure 11).

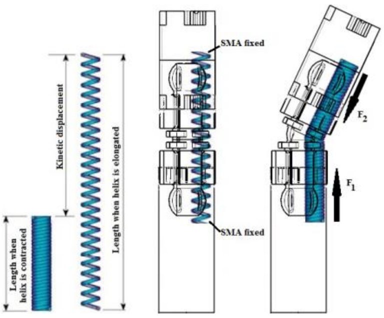

Figure 11. Operation of the SMA helix actuator

The links were fabricated by 3D printing in a rigid, high temperature-resistant resin (NanoCure, Envisiontec, Germany) and the joints in a soft elastomer material (TangoPlus, Objet Geometries, Israel). As a result of the combination of the rigid and soft materials, the finger bends around the centre of the soft structures. Furthermore, the flexible joints are of benefit, compared to a simple hinge, since it constitutes a simple way of creating multiple degrees of freedom.

Range of motion

The movement is similar to the one demonstrated in [29], however the rigid structures limit the range of motion. The helix was tested using current up to 500 mA, as greater current would considerably shorten the life of the SMA helix. The relation between the current and the range of motion is depicted in Figure 12.

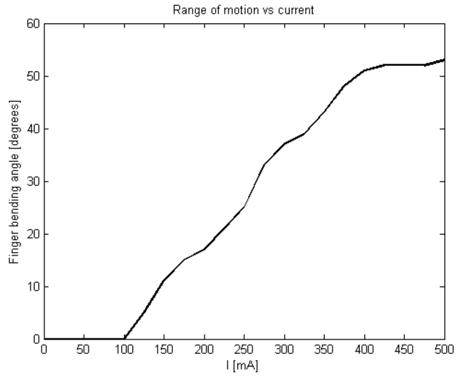

Figure 12. Relation between applied current and range of motion

It is also possible to improve the range of the angle generated by changing the length of the helix. For this reason, screw terminals were fitted inside the rigid links to enable the active length of the SMA actuators to be adjusted and achieve the maximum angular displacement. Figure 13 illustrates the maximum range of a joint when the actuator is under 350 mA ([-58°, 55°]) and 500 mA ([-63°, 66°]) of current.

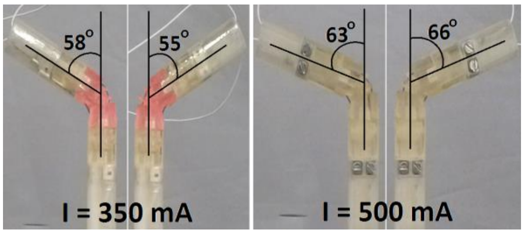

Figure 13. Angle measurement for current of 0.5 A / 0.35 A

Force measurement

Figure 14 shows the setup of the experiment for measuring the maximum force that can be applied, when using two links and one joint. A pressure sensor (FS01, Honeywell, USA) with a 3D printed hemisphere attached on top of it and a sensing range of 0-0.68 kg was used to measure the force. The hemisphere was added to the structure in order to distribute the applied force evenly on the sensing area and so that the output of the sensor is more consistent. The maximum force observed when activating one SMA, using a current of 350 mA, was 0.18 N. Although this measurement is approximate and possibly underestimates the real magnitude force applied due to the sensor's limitations, the applied force seems insufficient. It has been determined in prior studies [30] that force ranged between 2-8 N is required for pulling tissue (e.g. when suturing), while a force of maximum 48 N is needed for grasping a large needle. When two SMA helices were used simultaneously, the maximum observed force was greater (results summed up in table 2), but nevertheless inadequate. This suggests that a more complex configuration of SMA actuators needs to be considered, such as multiple SMAs acting in parallel.

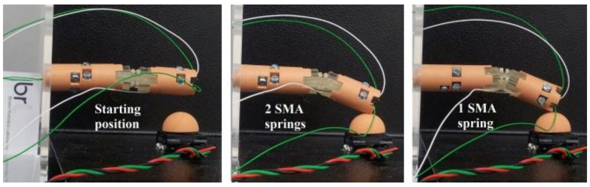

Figure 14. Testing applied force using one and two SMA helices

Table 2. Maximum applied Force

Actuated SMAs	Force (N)
single	0.18
both	0.25

Degrees of Freedom

As mentioned previously, two SMA actuators were used simultaneously to measure the combined produced force. The two pairs of antagonistic helices enable two independent DOFs, by enabling motion in two directions (pitch and yaw). Therefore the joint behaves as a universal joint, having the surface of a hemisphere as workspace.

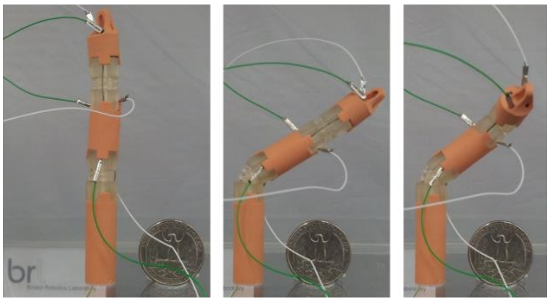

Figure 15. Actuation of each joint independently

The greatest advantage of the SMA actuators, besides their small size, is the fact that they allow independent movement for each joint. As illustrated in Figure 15, the second (top) joint moves without affecting the first one. This provides the opportunity for more elaborate and fine control and thus, precise movements. The combined motion of two fingers is demonstrated in Figure 16, where the last link (end-effector) is also shown in more detail. The design is such, that when the two end-effectors are united they resemble laparoscopic forceps, in order to make the grasp more efficient. Following from the fact that the control can allow the movement of the last link to be independent from the rest of the finger, it would be possible if needed, to use the fingers as standard forceps by joining the other two links of the fingers together.

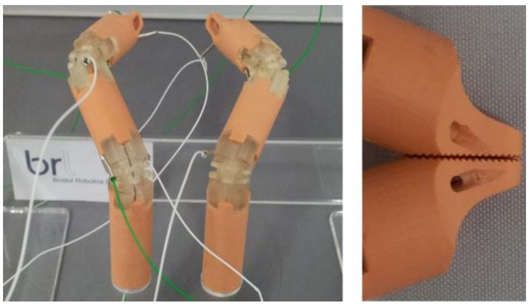

Figure 16. Two-finger grasping

An attempt for three-finger grasping is depicted in Figure 17, where three two-DOF fingers, in a layout resembling a thumb, index and middle finger, are grasping a sphere (20 mm diameter, 5 g) made out of compliant material. Although the type of grasping shown here is not similar to the way human fingers grasp an object due to the arrangement of the SMA helices in the structures, it was observed that the sphere was evenly grasped by all three fingers and as a result there was no compression. It could be extrapolated from this that a three-finger grasping is more stable and safe.

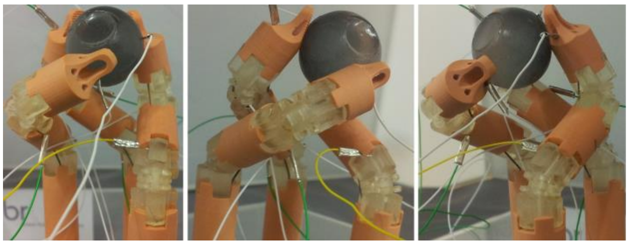

Figure 17. Three-finger grasping

Master controls

The proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints of the human fingers are hinge joints capable of only flexion and extension (1 DOF each). The metacarpophalangeal (MCP) joints at the base of the index and middle finger, however, are saddle joints, and hence capable of abduction and adduction (2 DOFs). The thumb can also be modelled by having two 1-DOF (interphalangeal-IP and metacarpophalangeal-MP) and one 2-DOF (Carpometacarpal-CMC) joints. The exoskeleton was designed according to this layout, so that it can follow the fingers' natural motion.

The angle of each joint is measured using two types of hall-effect sensors, MLX90316 and MLX90333 (Melexis, Belgium), measuring 1DOF and 3DOFs respectively. The 1-DOF sensor can give absolute angular position of a small magnet located parallel to the sensor in a rotary type joint. The 3-DOF sensor senses the magnet position anywhere in its surroundings, being suitable for a ball type joint. In order to simplify the exoskeleton design, the PIP and DIP of the index and middle fingers were considered coupled (as they are in the human hand). Therefore, instead of having different sensors for each joint, the exoskeleton carries only one sensor for the PIP joint, while the position of the DIP is calculated by the relationship between the PIP and the DIP given in [31]. The whole structure comprises seven sensors in total: three 2-DOF (MCPs and CPC) and four 1-DOF (PIPs, IP and MP).

Exoskeleton prototype

The computer-aided drawing with the main exoskeleton components is shown in Figure 18. Each exoskeleton joint is fastened to the hand with a flexible attachment and the joints are connected to each other via adjustable links. The MCP and CPC joints were designed as ball joints in order to reduce the bulkiness and the complexity of the component. The sensors are attached at the side of each joint on the non-contacting parts, as shown in Figures 19 and 20.

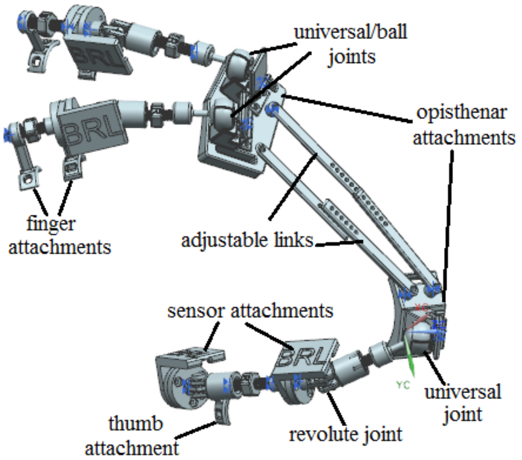

Figure 18. CAD drawing of the exoskeleton assembly

The typical ranges of motion of each joint in degrees are: 0-90° for the MCP, 0-110° for the PIP and 0-70° for the DIP. To ensure unrestricted motion, the range of the ball joint was set to be at least 90°. From the parameters in Figure 19, the range of the ball joint can be calculated as:

$$2\theta = 2(90 - \phi_1 - \phi_2) \ = 2\left(90 - sin^{-1}\frac{d}{R_2} - sin^{-1}\frac{r}{R_2}\right)$$

where $R_2 = 6\,mm$, $d = 3\,mm$ and $r = 1.5\,mm$.

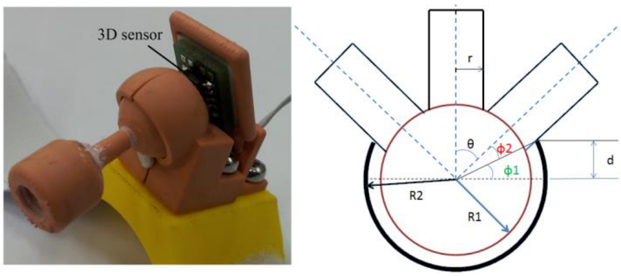

Figure 19. Ball joint prototype and range of motion calculation

The joints are connected to each other via double threaded links (Figure 20). One side has a left-hand thread, while the other has a right-hand thread so that, by turning the link, it can be extended (clockwise) or shortened (anti-clockwise).

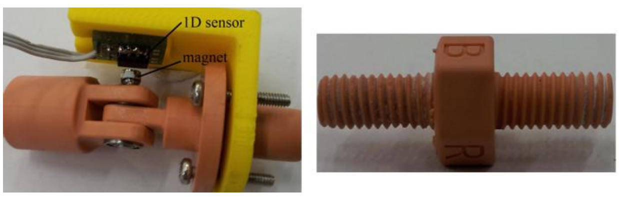

Figure 20. Revolute joint and double threaded adjustable link

Discussion

The analysis emerging from the focus groups confirmed the preceding results from the survey regarding the cost as well as the benefits of the Da Vinci Surgical System. Their responses about its cost, combined with the fact that the percentage praising the system for its vision capabilities is high, could mean that not many surgeons would consider using the Da Vinci System if they had a good 3D vision system during traditional laparoscopy.

In addition, not all surgeons performing robotic surgery have experience in laparoscopic techniques. If, in fact, it is not necessary to be trained in laparoscopy before moving on to robotic systems, the questions to be asked would be, “why do robotic instruments have to resemble laparoscopic instruments? Are they merely an adjunct to traditional MIS [32]”? It is needed to go beyond the incremental results of the current robotic methods and adopt more radical approaches. Manipulating tissue with laparoscopic instruments (e.g. forceps) is more difficult than using the hands; organs and tissue slipping from the grasp of the instruments is common, and perhaps this indicates that the design of laparoscopic graspers is not as effective as it could be [33].

Justified by the survey, the prototype for surgical robotic instrumentation presented here, focuses on the concept of multi-port MIS. It also attempts to attenuate the difference in performance between junior and senior surgeons as a result of the difficulty in transition from open to MIS techniques, by reducing the complexity of training. The fact that it imitates the natural motion of the hand gives it the potential to turn the training of a surgeon for MIS into a shorter and less strenuous process, while offering even more intuitive and efficient manipulation. It meets the requirements arising from the survey such as attention to improved articulation and ergonomics, while the feedback from surgeons during the focus groups was positive. The user-interface (master controls-exoskeleton in Figure 2) simplifies the control, while the surgeon can choose his/her preferred posture.

Therefore, it can be stated that the sensory hand exoskeleton presented in the previous section meets the design requirements. The double thread links not only make the mechanism adjustable to a variety of hand sizes, but also allow the exoskeleton to be lightweight (approx. 130 gr), without added material for modifications as in [16]. Furthermore, each of its joints covers a range of motion similar to, or greater than, that of a human hand, which ensures natural unrestricted hand motion and comfort. The overall structure is as compact as possible and has twelve DOFs, ten of which are actively sensed while the other two can be calculated from the neighbouring joints. The next version of the exoskeleton will also include sensors for wrist motion tracking, in contrast to the methods used in [19-20], where this would not be possible. The exoskeleton has been fabricated using 3D printing (NanoCure, Envisiontec, Germany). Figure 21 shows part of the exoskeleton fitted on the side of the index finger and the electronics attached to the wrist. Sensor processing electronics will be placed in a compact box, the size of a hand watch.

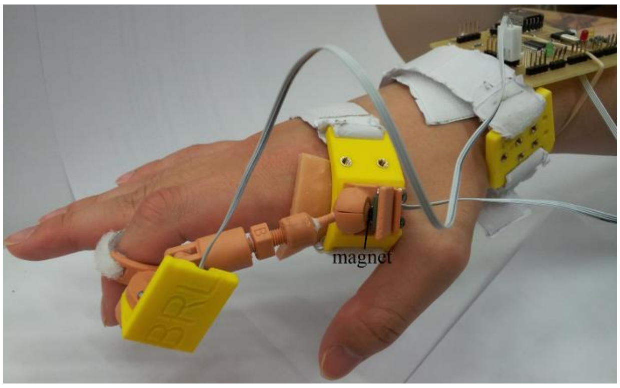

Figure 21. Testing the exoskeleton on one finger

In the first phase of our investigation, the surgeon will explore use of the exoskeleton to manipulate virtual objects. The sensory electronics will be connected to a PC via USB and the output of the sensors fed into a 12-DOF hand kinematic model. The user will wear the exoskeleton and the movements of his/her fingers will be simulated in real-time. This will form the basis of a surgical simulation environment, where the surgeon will be able to test the concept of controlling hand-like instruments as described in [17]. The accuracy of the structure needs to be tested and the teleoperation suitability will be evaluated in our future work. At that stage, the exoskeleton will be connected directly to two corresponding surgical hands.

The prototype of the instruments was also built through 3D printing, a method becoming ever more affordable and accessible, especially as it is possible to print rigid and flexible materials on the same printer. In future, 3D printing could be used to fabricate low cost, single use, bespoke surgical instruments, which can be custom made to suit the ergonomics and operating style of a particular surgeon or to fit an individual patients anatomy.

The actuating methods of the instruments evaluated in this paper seem to be inadequate for the surgical grasping tasks. Although the miniature size and the relatively low cost of the SMA actuators make them advantageous compared with other methods, the produced force is too limited. In future, the finger structure will be altered to accommodate a cable-driven mechanism. In order to minimize the complexity of the structure, the last two joints of each finger (excluding the thumb) can be considered coupled, as they are in the human hand. Furthermore, the concept of a three-finger instrument and its grasping quality will be explored and evaluated.

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